AIP Journal of Applied Physics

Room temperature rectifying characteristics of epitaxial $Y_1Ba_2Cu_{3-x}Zn_xO_{7-\delta}$ ($x = 0.0, 0.2$) and Nb : $SrTiO_3$ (Nb: 0.05%, 0.1%, 0.5%) heterojunctions

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Citation: Journal of Applied Physics **99**, 043906 (2006); doi: 10.1063/1.2172867
View online: http://dx.doi.org/10.1063/1.2172867
View Table of Contents: http://scitation.aip.org/content/aip/journal/jap/99/4?ver=pdfcov
Published by the AIP Publishing

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(Received 1 December 2005; accepted 18 December 2005; published online 24 February 2006)

We report on the fabrication and electrical characterization of epitaxial metal-semiconductor junctions between $Y_1Ba_2Cu_3O_{7-\delta}$ (YBCO) (optimally doped and Zn doped) and (001) Nb:$SrTiO_3$ with different Nb concentrations (0.05%, 0.1%, and 0.5%). The current-voltage characteristics of such epitaxial junctions are nonlinear and rectifying, and these are dramatically enhanced with decreasing Nb concentration and Zn doping. Indeed, for the case of 0.05% Nb:STO, reverse breakdown voltage as high as −18 V(−28 V) is realized for optimally doped (Zn doped) YBCO. These data are analyzed within the framework of thermionic emission/diffusion models for Schottky and metal-insulator-semiconductor-type junctions. © *2006 American Institute of Physics*. [DOI: 10.1063/1.2172867]

The field of oxide electronics has gained considerable momentum during the past few years with the enhanced ability to grow and examine high quality oxide-oxide interfaces. Importantly, such systems can be realized with high carrier concentrations and can therefore be implemented even over nanoscale without serious carrier statistics issues. Such interfaces are now also being looked at as materials with unique properties[1–3] capable of supporting device functions. Amongst the various interface systems, the oxide-based *p*-*n* junctions and metal-semiconductor (Schottky) interfaces are receiving considerable attention recently[4–14] in view of their projected use in different applications. In this work we have examined the growth and transport properties of the interface between $YBa_2Cu_3O_{7-\delta}$ (YBCO) and an *n*-type oxide semiconductor Nb doped $SrTiO_3$ (NSTO). Specifically, the influence of the Nb concentration in NSTO and Zn doping in YBCO on the room temperature nonlinear rectifying characteristics is examined. Over a decade ago, Hasegawa *et al.*[15] had studied the properties of the contact between the high T_C superconductor Er–Ba–Cu–O and Nb:STO, however, the T_C (zero resistance) of their optimally doped film was only 69 K much lower than the expected 92 K.[16] In our optimally doped films studied in this work the T_C is ~91 K which implies better film quality and therefore improved normal state properties of interest to this work. The basic rectifying character of such interfaces is also shown in other works.[17,18]

In our experiments commercially procured (Crystek) high quality single crystalline (001) Nb doped $SrTiO_3$ substrates (Nb concentrations of 0.05%, 0.1%, and 0.5%) were used for film growth. Here the percentage refers to wt %. The YBCO films were grown by pulsed laser deposition (PLD) technique. A pulsed KrF excimer laser was used for ablation. The corresponding energy density and pulse repetition rate were 1.8 J/cm^2 and 10 Hz, respectively. The films of optimally doped YBCO were grown at 200 mTorr oxygen pressure at the substrate temperature of 800 °C and then cooled to room temperature in oxygen pressure of 400 Torr. This growth condition is known to yield films with good crystallinity and superconducting properties.[19–21] A separate set of Zn doped YBCO films ($YBa_2Cu_{3-x}Zn_xO_{7-\delta}, x=0.2$) was grown at 750 °C at 130 mTorr oxygen and cooled under 400 Torr oxygen. This low temperature growth procedure was used to control the Zn loss at high temperature as suggested by Ogale *et al.*[22] The films were characterized by x-ray diffraction (structural quality and lattice parameter), Rutherford backscattering (RBS) channeling (crystalline quality, composition, and thickness), and four-probe electrical measurements. For the standard RBS and ion channeling measurement 3.05 MeV He ions were used. Indium contacts were made to NSTO, while In–Ag contacts were made to the YBCO layer to ensure ohmic contact characteristics for the respective electrodes. No lithography was used and the devices were several mm^2. The resistivity values for the superconductor films were measured on a pure $SrTiO_3$ (001) substrate, on which films were grown concurrently with those on NSTO, to avoid the interference of the conductivity of NSTO in the measurement.

The x-ray diffraction (XRD) pattern for a typical film (not shown) could be indexed to the (00ℓ) family of the 123

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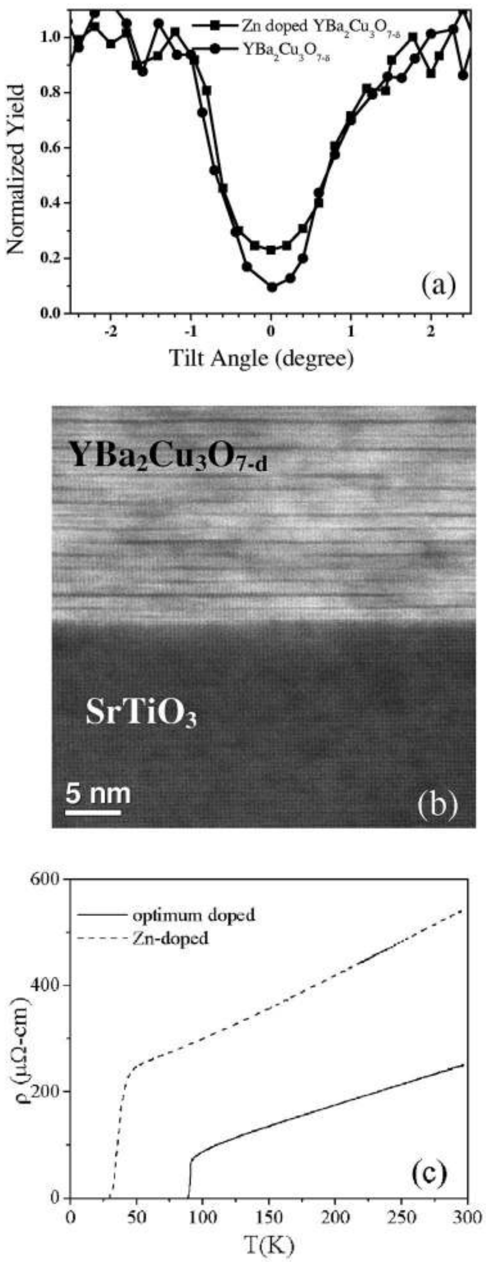

FIG. 1. (a) RBS angular scans for the pure (optimally doped) and Zn doped samples: the minimum channeling yields ($\chi_{min}\%$) for the pure and Zn doped cases are about 8% and 20%, respectively; (b) high resolution cross-section scanning transmission electron microscopy (STEM) data for an optimally doped film; (c) in-plane resistivity (ρ_{ab}) as function of temperature (T) for the optimally doped and Zn doped YBCO films.

superconducting phase up to $\ell=11$ indicating their c-axis orientation.[19–22] Figure 1(a) shows the representative RBS angular scans for the optimally doped and Zn doped samples. Good minimum channeling yields (χ_{min}) of about 8% and 20% are realized for the two cases, reflecting the high crystalline film quality. The higher yield in the case of Zn doped sample possibly reflects local distortions due to the dopants which are very sensitively reflected by the RBS channeling technique. Also, as stated earlier the growth temperature for Zn:YBCO had to be kept somewhat lower to avoid loss of Zn.

The high quality of our interfaces was further ensured by high resolution scanning transmission electron microscopy

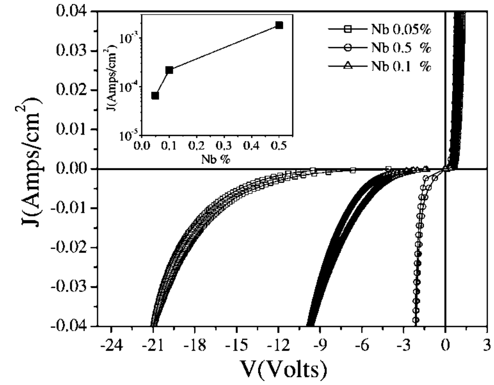

FIG. 2. The *I*-*V* characteristics of the junctions of optimally doped YBCO films on NSTO for three different Nb concentrations. The inset shows the change in the reverse bias leakage current at −1 V as a function of Nb concentration.

(STEM); the representative data for an optimally doped film being shown in Fig. 1(b). The interface is clearly seen to be abrupt and epitaxial. The stacking fault-type features running parallel to the interface are well known in the highest quality films.[23] We also performed chemical analysis of the films across the interface using electron-energy-loss spectroscopy (EELS) and found that the interfaces are also chemically sharp within subnanometer scale. The details of these studies will be reported separately.[24] The data for in-plane resistivity (ρ_{ab}) as function of temperature (T) for the two cases of YBCO films are shown in Fig. 1(c). The properties are clearly as expected in terms of the residual resistively ratio and the sharpness of transition.

In Fig. 2 we show the *I*-*V* characteristics for the junctions employing pure YBCO films grown on NSTO for three different Nb concentrations. It can be clearly seen that decrease in Nb concentration leads to dramatic improvements in the characteristics in terms of the reverse threshold voltage and reverse leakage current as well as the forward bias features. The reverse voltage increases from about −2 to −18 V as the Nb concentration is lowered by an order of magnitude from 0.5% to 0.05%. This could be attributed to the sensitivity of the avalanche breakdown effect to Nb concentration. The inset shows the change in the reverse bias leakage current at −1 V as a function of Nb concentration. For 0.05% Nb:STO the reverse leakage current density is as low as 6×10^{-5} A s/cm^2 even for our large area junctions. The fact that such Nb concentration dependence is seen implies that the junction transport involves carrier diffusion in addition to thermionic emission, since for the latter case alone such dependence is not expected.[25] This is understandable since at lower Nb concentrations the semitriangular carrier depletion profile is expected to widen on the semiconductor side thereby involving carrier diffusive transport. Widening of the effective barrier width is also the reason for the substantial reduction in the reverse leakage current. The forward current density at half of the turn on voltage is of the order of 10^{-11} A s/μm^2, which is clearly within the acceptable technology regime even for our large area diodes. The hysteretic features are noted in the characteristics, which have also been observed in previous works[26–29] on perovskite matrices and attributed to complex effects involving

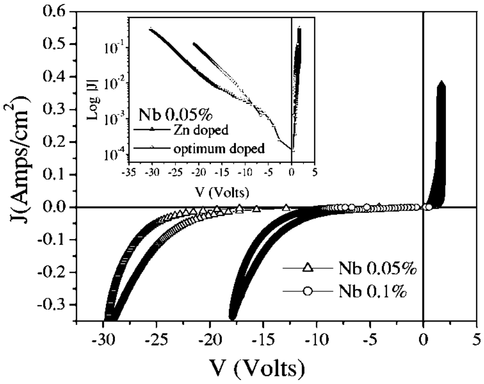

FIG. 3. The *I-V* characteristics for the $YBa_2Cu_{2.8}Zn_{0.2}O_{7-\delta}$ and Nb: $SrTiO_3$ (Nb: 0.05%, 0.1%) heterojunctions. The inset compares the log $[A_{bs}(J)]$ vs V data for two cases of pure YBCO and Zn:YBCO for junctions on 0.05% Nb:STO.

interface trap states, oxygen vacancy defects, and their slow dynamics under current and field, driven by electrochemistry.[30–33] Such effects can lead to distribution of charge in the interfacial region affecting the band lineup and tunneling probability. The related physics and the temperature dependence of the characteristics will be discussed separately in a long paper.[34] While lowering of Nb concentration in NSTO does improve some aspects of the characteristics dramatically, a separate study may be required to evaluate whether the hysteretic features limit the practical use of such junctions and how the same can be minimized.

In Fig. 3 we show the characteristics for the $Y_1Ba_2Cu_{2.8}Zn_{0.2}O_{7-\delta}$ and Nb:$SrTiO_3$ (Nb: 0.05%, 0.1%) heterojunctions. When compared to the data in Fig. 2 one can clearly see a significant improvement in the transport features for the Zn:YBCO based junction over the pure YBCO based junction, some of which could arise from the higher resistivity of the Zn:YBCO electrode as compared to pure YBCO. Indeed, the reverse voltage increases from about −18 V for the pure YBCO based junction to −28 V for the Zn:YBCO based junction for 0.05% Nb:STO electrode. The reverse leakage current density at −1 V is $\sim 1.5 \times 10^{-5}$ A s/cm^2 even for our large area junctions. This is also a factor of 4 lower than similar junctions based on pure YBCO. The forward current density at half of the turn on voltage for the Zn:YBCO/0.05% NSTO diode is even less than 10^{-11} A s/μm^2, a clear improvement over the diode is based on pure YBCO.

The primary effects of Zn doping[35] and related scattering are to add a nominally temperature independent contribution to the transport scattering rate. However, a small increase in the average slope of $d\rho_{ab}/dT$ can be noted and the same can be attributed to a decrease in carrier concentration. Each Zn ion is suggested to represent a scattering cross section of a diameter of about 4.2 Å (encompassing four oxygen neighbors), and this strong scattering may well be one of the causes of the rapid suppression of T_C with Zn incorporation. Zn is a nonmagnetic impurity, but it induces a magnetic moment in CuO_2 plane when substituted at the Cu site, the precise value of the moment being dependent upon oxygen content. While it is difficult to specify the precise reasons for the observed improvements in the *I-V* characteristics, some possibilities can be suggested. A decrease in the carrier concentration and enhanced scattering on the YBCO side of the junction due to Zn doping could lead to a modification of the barrier profile favorable to the rectifying behavior. It is also possible that a small amount of Zn may diffuse across the barrier into NSTO clearing some electronic traps and leading effectively to an ultrathin insulating STO between Zn:YBCO/NSTO. This could in fact render a metal-insulator-semiconductor (MIS)-type Schottky character to the junction.[25] In the inset of Fig. 3 we compare ln$[A_{bs}(J)]$ vs V data for two cases of pure YBCO and Zn:YBCO with 0.05% Nb:STO. The clear differences in the nature of dependence suggest that in the latter case MIS Schottky behavior is a distinct possibility.

We studied the Nb:Ti ratio near the surface of the NSTO substrate (for 0.5% Nb case for which, a good signal to noise ratio was obtained) by x-ray photoelectron spectroscopy (XPS) for the cases of the as-received substrate and another annealed at 800 °C in 200 mTorr oxygen for about half an hour followed by slow cooling in 400 Torr oxygen. The latter recipe was used to simulate the conditions to which a typical substrate is subjected to during the YBCO growth. The Nb:Ti ratio was found to be nearly unaffected, implying that a thin Nb depleted layer does not seem to form by the Nb diffusion in the substrate itself during film growth. The possibility of formation of an ultrathin semi-insulating layer at the interface[18] may thus result from a degree of interface diffusion as suggested earlier.

In conclusion, epitaxial metal-semiconductor junctions between $Y_1Ba_2Cu_3O_{7-\delta}$ (optimally doped and Zn doped) and (001) Nb:$SrTiO_3$ (NSTO) with different Nb concentrations (0.05%, 0.1%, and 0.5%) are fabricated and studied. The change in the concentration of Nb in the NSTO substrate and Zn doping in YBCO affects the rectifying current-voltage characteristics of such epitaxial junctions significantly. Indeed, for the case of 0.05% Nb:STO a reverse breakdown voltage as high as −18 V (−28 V) is realized for optimally doped (Zn doped) YBCO. The reverse leakage current density at −1 V is of the order of 10^{-5} A ps/cm^2 in all cases and could be reduced by limiting the junction area.

One of the authors (W.R.) would like to thank the Fulbright Commission for support. The work was supported by UMD NSF-MRSEC under Grant No. DMR 00-80008. The microscopy work of another author (N. D. B.) was supported by NSF under Grant No. DMR-0335364 and performed in the National Center for Electron Microscopy at Lawrence Berkeley National Laboratory supported by the Department of Energy under Contract No. DE-AC02-05CH11231. Thanks are also given to B. Varughese for XPS measurements.

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